NASA Dryden: Flight Loads Lab Capabilities and Mass Properties Testing

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Huntington Beach, CA

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Topics

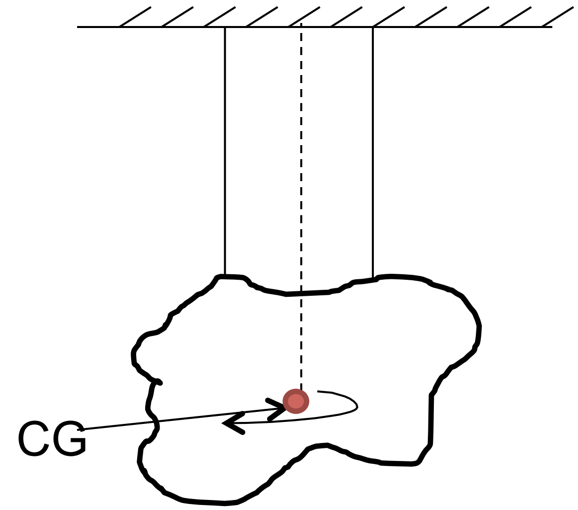
- Flight Loads Lab Capabilities
- Latest Conventional Moment of Inertia (MOI) Tests
  - Bifilar, Simple Pendulum
  - Iron Cross and X-48B Testing
  - Frequency/Amplitude Relationships
    - Phase 1 Testing vs. Phase 2 Testing
- Dynamic Inertia Measurement (DIM) Method
  - Concept Overview
  - Large-Scale DIM Test
  - Lessons Learned
  - Conclusions

NASA Dryden's Flight Loads Laboratory

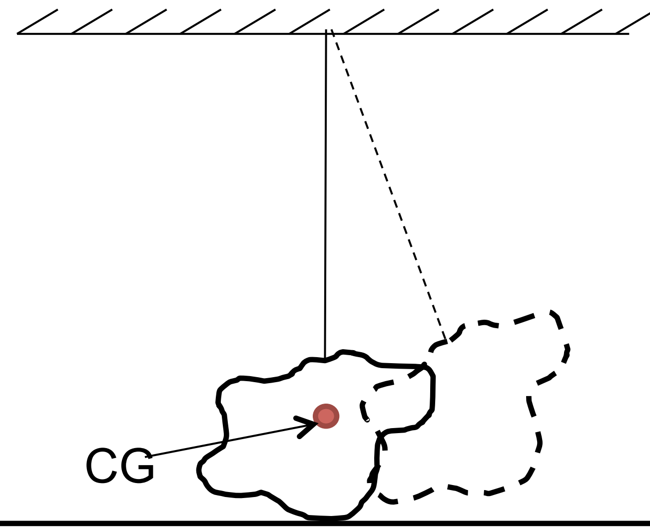
Conventional Mass Properties Testing

Conventional MOI Testing

- Conventional MOI Test Techniques include:
  - Bifilar Pendulum: Dual-wire suspension, oscillates about CG in one axis
    - Must accurately know longitudinal CG to evenly balance load across both bifilars
  - Simple Pendulum: Single or multiple suspension, oscillates about a non-CG point in one axis
    - Must use parallel axis theorem to take out transfer inertia
    - Accuracy suffers because inertia about swing point is relatively large



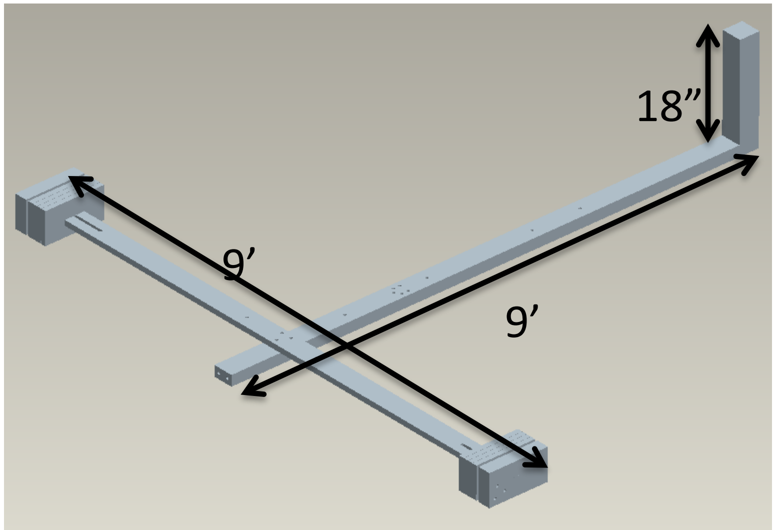
Bifilar Pendulum Swing



Simple Pendulum

X-48B and Iron Cross MOI Test (Phase 1)

- X-48B MOI Testing was desired to solve discrepancy between aero models and flight data.
  - MOI Errors were identified as a prime cause for this discrepancy.
- Iron cross test article built to quantify accuracy/uncertainty
  - Very simple, easy to analyze inertia values.
- Once conventional methods were analyzed, the same test setup would be used on X-48B.
  - Accuracies/Uncertainties should remain constant due to similarities in test articles.



Iron Cross CAD Model

Iron Cross (Assembled)

Iron Cross MOI Testing – Phase 1

Independent MOI testing was performed at Space Electronics

Bifilar Pendulum/ Longitudinal CG Test

Simple Pendulum (Roll)

Simple Pendulum (Pitch)

Iron Cross MOI Results – Phase 1

Variable	%Error/Abs. Difference
Test Article Weight	.04%
Longitudinal CG (A/C CS)	.051 inches
Vertical CG (A/C CS)	.116 inches
*Yaw Inertia (Izz, lbs*in^2)*	1.47%
*Roll Inertia (Ixx, lbs*in^2)*	2.99%
*Pitch Inertia (Iyy, lbs*in^2)*	NA

Comparison Between Space Electronics Data and Analytical Data

Summary of Data	% Error/Abs. Difference
Test Article Weight	0.29 %
Longitudinal CG (A/C CS)	-0.03 inches
Vertical CG (A/C CS)	-0.009 inches
*Yaw Inertia (Izz, lbs*in^2)*	2.13 %
*Roll Inertia (Ixx, lbs*in^2)*	5.73 %
*Pitch Inertia (Iyy, lbs*in^2)*	2.39%

Comparison Between Bifilar/ Simple Pendulum Methods and Space Electronics Data

X-48B MOI Testing – Phase 1

- Using the same setup as on the iron cross, the X-48B underwent Lateral, Longitudinal, and Vertical CG Testing
- It also underwent Bifilar Pendulum and Simple Pendulum Testing in Yaw and Pitch/Roll.

Bifilar/Lateral/Longitudinal CG Testing

Vertical CG Testing

Simple Pendulum (Roll)

Simple Pendulum (Pitch)

X-48B MOI Results – Phase 1

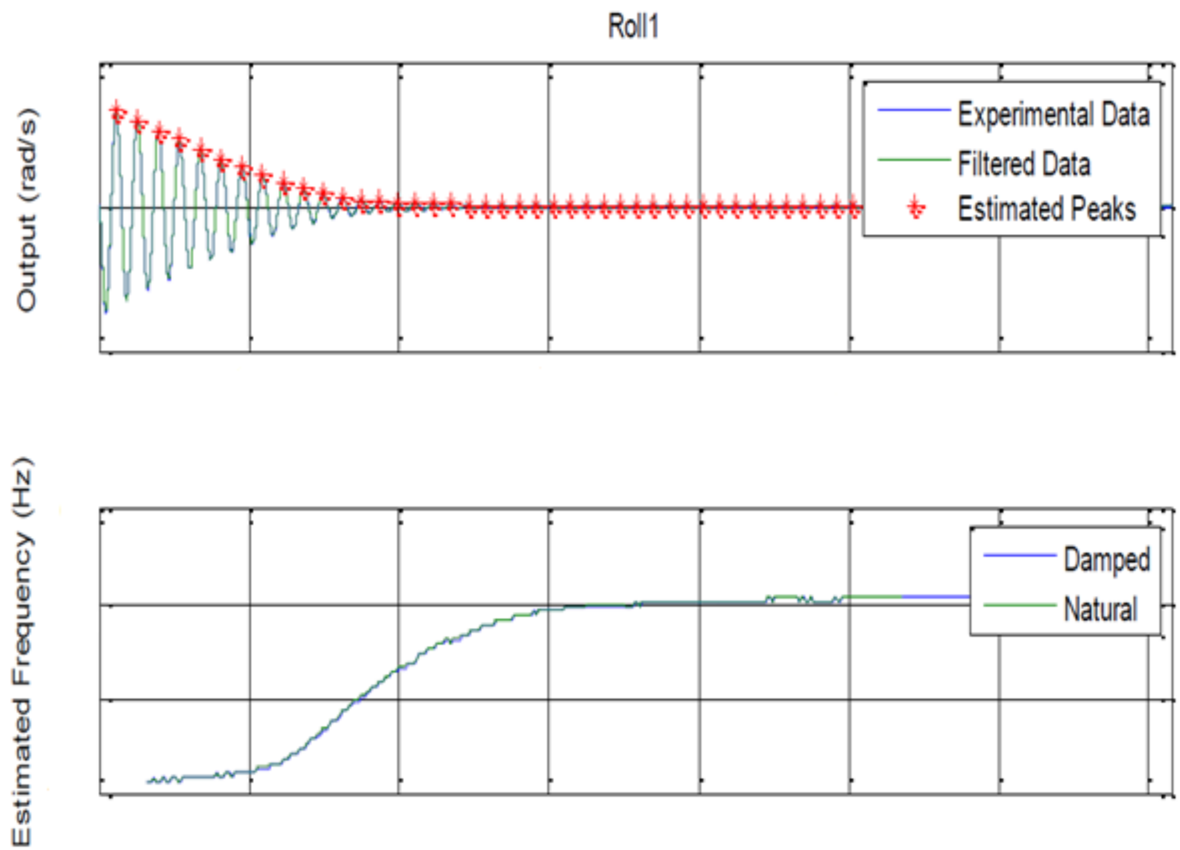
- The roll and pitch inertia terms indicated by the experimental results are very different from the predicted results.
- Digging deeper into the frequency data obtained by the onboard IMU (initially a backup system) yields surprising results
  - Initial results obtained from stopwatch data

Variable	%Error/Abs. Difference
*Yaw Inertia (Izz, lbs*in^2)*	9.28
*Roll Inertia (Ixx, lbs*in^2)*	56.18
*Pitch Inertia (Iyy, lbs*in^2)*	65.01

Comparison between Predicted and Experimental MOI Data

X-48B MOI Results – Phase 1

- It appears as though a frequency shift is occurring as the amplitude of the swing changes.
  - Frequency only varying a small amount (in this case, <.03 hz)
  - Simple pendulum inertia equation is so sensitive that this can result in a shift of as much as 70% in the inertia values.
- Upon further analysis, the pitch data showed even worse frequency shifts.



Time History and Frequency Plot for Roll Swing

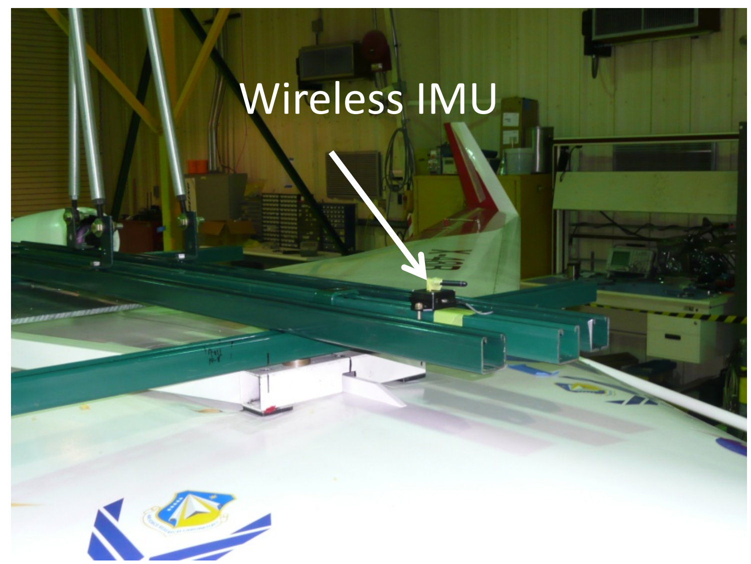
Phase 2 MOI Tests

- Why was the frequency shift happening?
  - Many theories, none proven
- Second phase of MOI Testing required to determine:
  - What is causing the frequency shift
  - Can the frequency shift be corrected for
- Attaching an IMU to the iron cross could determine if the results could be “filtered” by removing data where frequency shifts are occurring.
  - It appeared as if smaller amplitude data produced worse results than larger amplitude data, which goes against traditional thinking
  - Frequency analysis would only be performed over data from ~10 degrees maximum oscillation to ~ 3 degrees maximum oscillation

Phase 2 MOI Tests

- In addition to focusing on larger amplitude swings, a new setup was devised for pitch swings.
  - In the initial tests, the pitch swings showed significant cross coupling of pitch, yaw, and roll.
  - New setup was designed to alleviate cross coupling

Adjusted Setup for Pitch Swings



Phase 2 MOI Testing

- Other factors investigated were:
  - Length of suspension system: The simple pendulum equations are sensitive to length (due to the mass rotating about a point other than the CG). By shortening the length, theoretically the accuracy of the calculated inertia should increase.
  - If the iron cross saw frequency shifts as well: If so, then aerodynamic effects could be eliminated as the primary source of the shift.

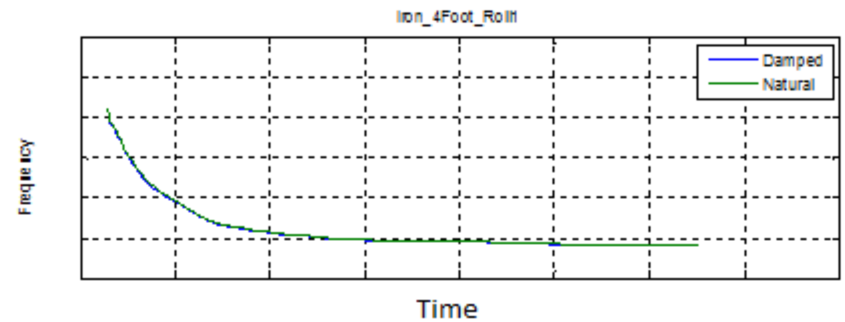
$$I_{combined} = I_{TA} + I_{rig} + m_{TA} l^2$$

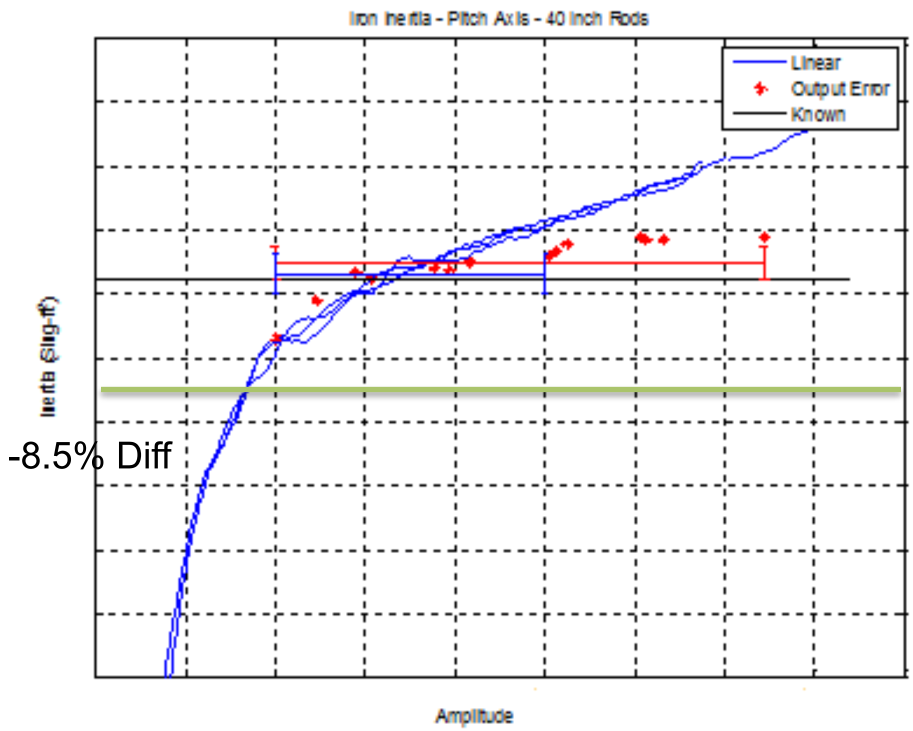
$$I_{TA} = I_{combined} - I_{rig} - m_{TA} l^2$$

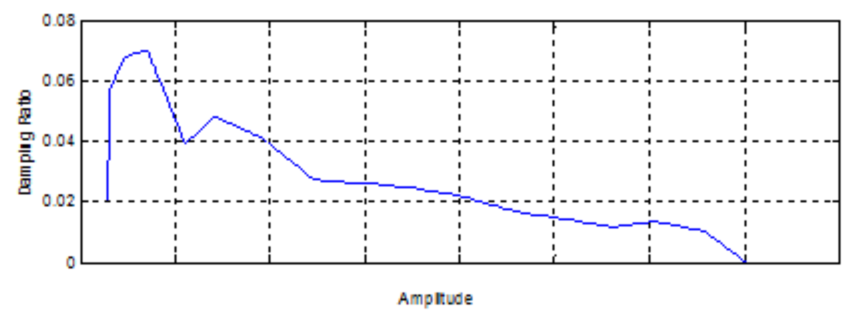
High Sensitivity to length of suspension system

Phase 2 MOI Testing Results

- The iron cross did indeed see a frequency shift (same order of magnitude as X-48B)
- Damping ratio was negligible





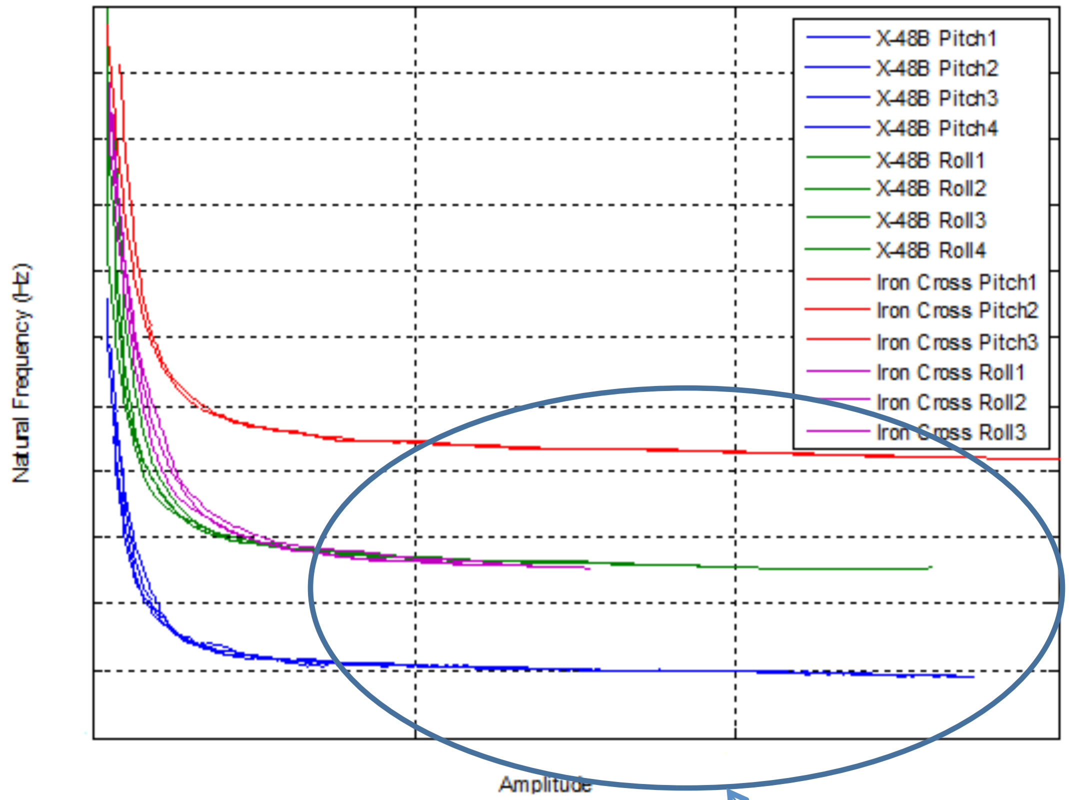


- Calculated inertia values as a function of amplitude are shown in the figure to the left.
- Inertia values blow past the predicted values (i.e., not asymptotically approaching, etc.)

-16% Diff

Phase 2 MOI Testing Results

- A comparison of all the X-48B and Iron Cross pitch and roll swings are shown to the right.
- Nearly identical trends occurring across all test scenarios.
- In theory, using the data where the frequency shift is negligible (flat region) should provide better results.



Flat region is "good data", where frequency shift is negligible

Phase 2 MOI Test Results

- Iron Cross results are very consistent with original results.
  - This time, roll inertia is more in line with pitch inertia. This seems to point that the original roll inertia swings suffered from the same frequency shift that the X-48B did, while pitch inertia was less affected.
- X-48B results are more in line with the predicted values.
- Unknown cause of frequency shifts at this time

Iron Cross Inertia Values	*Phase 1 % Error*	*Phase 2 % Error*
*Yaw Inertia (Izz, lbs*in^2)*	2.13 %	2.13
*Roll Inertia (Ixx, lbs*in^2)*	5.73 %	-2.2
*Pitch Inertia (Iyy, lbs*in^2)*	2.39%	-2.75

X-48B Inertia Values	*Phase 1 % Error*	*Phase 2 % Error*
*Yaw Inertia (Izz, lbs*in^2)*	9.28	9.28
*Roll Inertia (Ixx, lbs*in^2)*	56.18	-4.04
*Pitch Inertia (Iyy, lbs*in^2)*	65.01	-2.95

Summary

- Bifilar pendulum, if great care is taken to provide accurate measurements, is very accurate (in this case, ±2.13%).
- Simple pendulum:
  - Same level of care must be taken in setup to ensure accurate measurements
  - IMU must be used to filter out areas of frequency shift
  - Uncertainty can be as low as ± 2%
- Both methods require meticulous measurement of primary variables (length, weight, frequency)
- In order to get all three moments of inertia using these methods, multiple test setups/fixturing must be designed and implemented.
  - Time and cost increase as a result

Dynamic Inertia Measurement (DIM)

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DIM Concept

- Use force excitation and measure structural response via accelerations to determine mass properties
  - Similar to Ground Vibration Test (GVT) techniques
  - Focuses on data off-resonance ("mass lines")
- Possibility of obtaining all mass properties with one set-up
  - Mass
  - Center of Gravity: X_{CG}, Y_{CG}, Z_{CG}
  - Moments of Inertia: I_{XX}, I_{YY}, I_{ZZ}
  - Products of Inertia: I_{XY}, I_{XZ}, I_{YZ}
- Little additional effort required beyond GVT
  - Same test set-up (soft suspension system, shakers, data acquisition equipment, etc.)
  - Similar data processing

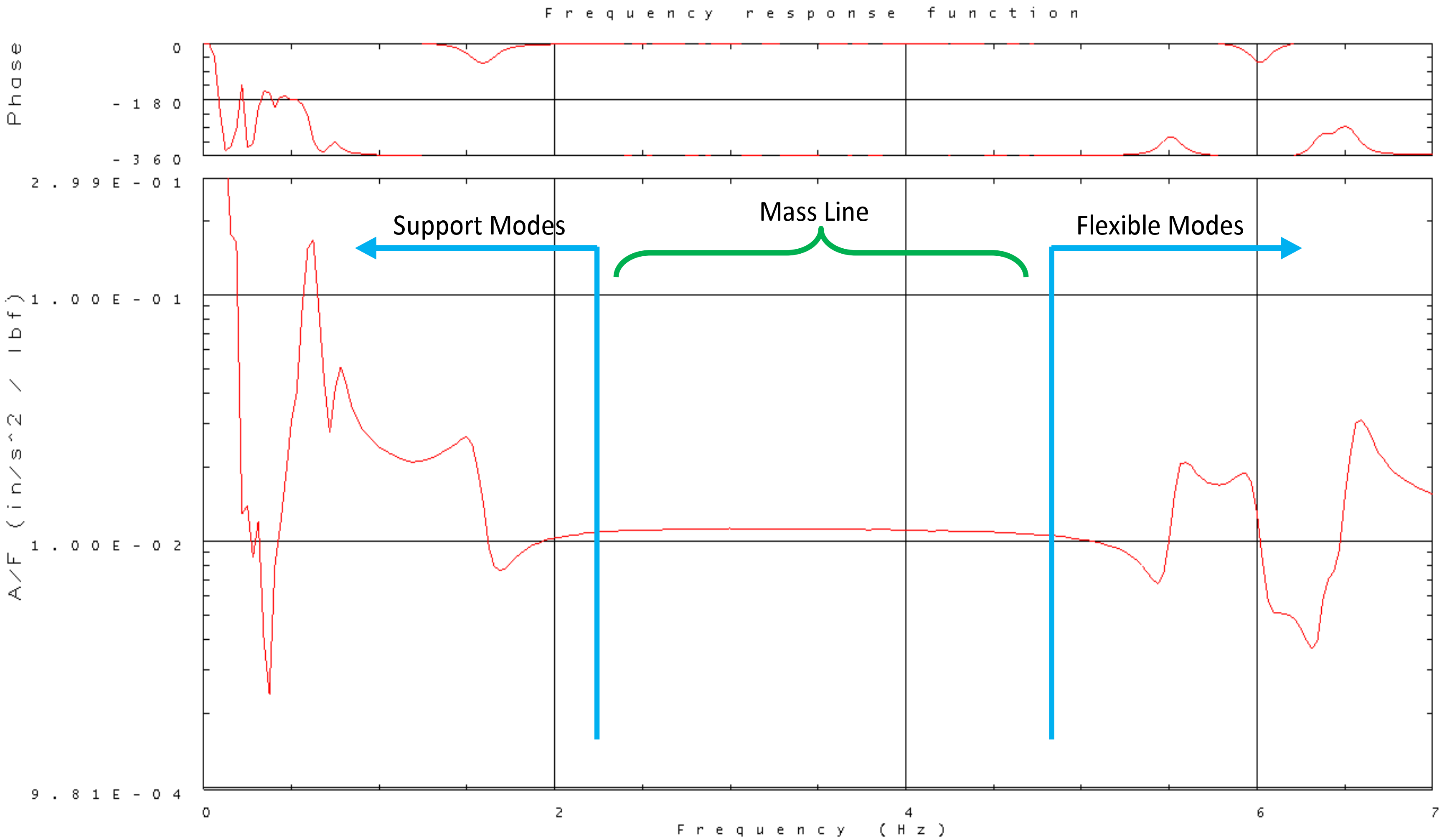
DIM Theory

- Based on Newton's Second Law (F=ma)
  - Expanded to 6 degrees of freedom

$$\begin{Bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{Bmatrix}_P = \begin{bmatrix} m & 0 & 0 & 0 & mZ_{CG} & -mY_{CG} \\ 0 & m & 0 & -mZ_{CG} & 0 & mX_{CG} \\ 0 & 0 & m & mY_{CG} & -mX_{CG} & 0 \\ 0 & -mZ_{CG} & mY_{CG} & I_{xx} & -I_{xy} & -I_{xz} \\ mZ_{CG} & 0 & -mX_{CG} & -I_{yx} & I_{yy} & -I_{yz} \\ -mY_{CG} & mX_{CG} & 0 & -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix} \begin{Bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \\ \ddot{\theta}_x \\ \ddot{\theta}_y \\ \ddot{\theta}_z \end{Bmatrix}_P$$

- Must measure all reaction loads
  - Requires 6 degree-of-freedom (6-DOF) load cells at suspension interface points
- Data computed as Frequency Response Functions (FRFs)
  - Mass property values are determined at each spectral line

DIM Analysis Window



DIM Testing Background

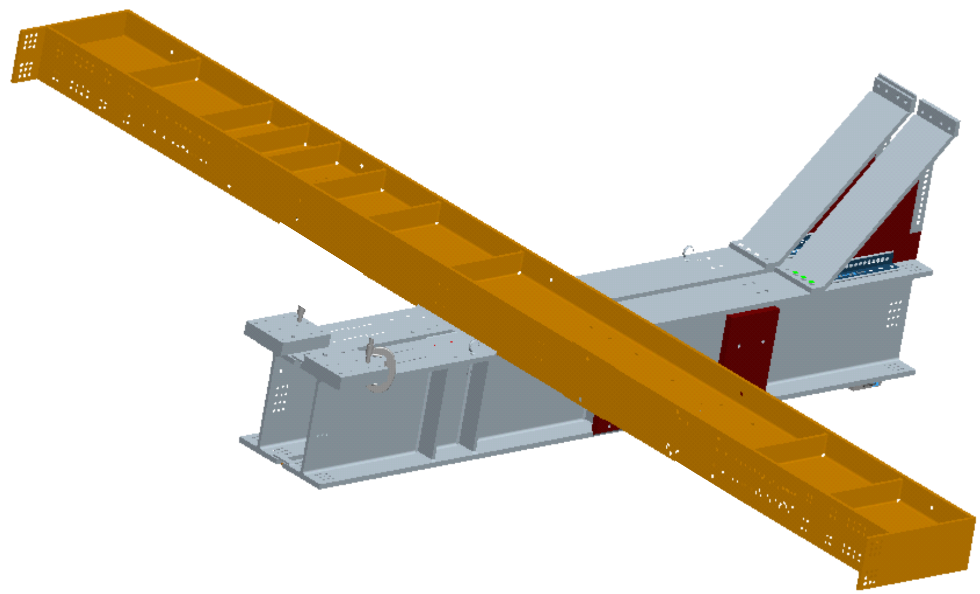
- Successfully performed on small (desktop size) test articles
- Last attempted on large vehicles on X-38
  - Unexpected flexible modes hindered successful usage of spatial filtering
  - Unexpected suspension system modes also affected spatial filtering
  - Instrumentation issues with 6-dof load cells and excitation
- This attempt aimed at solving issues with large test article
  - Instrumentation required:
    - Seismic accelerometers – for higher sensitivity
    - 6-DOF load cells at soft suspension system interface points
    - Laser tracker to record DIMM instrumentation orientation
  - Preferred excitation methods

DIM Test Overview

- Partnership between NASA Dryden, ATA Engineering Inc., and Dave Brown (University of Cincinnati)
  - Dryden created test article, provided equipment and executed test
  - ATA created the analysis scripts and performed analysis
  - Dave Brown advised on test and analysis techniques
- New 6-DOF load cell created by PCB
- Test article created out of steel I-beams
  - 17,000 lbs
  - Approximate shape of aircraft
- Mass properties measured:
  - Conventionally (bifilar pendulum, X_{cg} and I_{zz})
  - Using DIM method

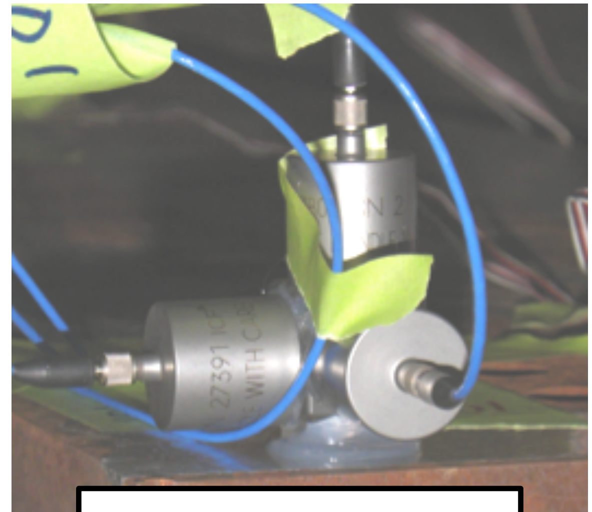
Conventional Testing

- Test frame was designed and built to suspend DIM test article
- Bifilar method used to measure X-cg and yaw-inertia
- CAD model was updated to match measured values

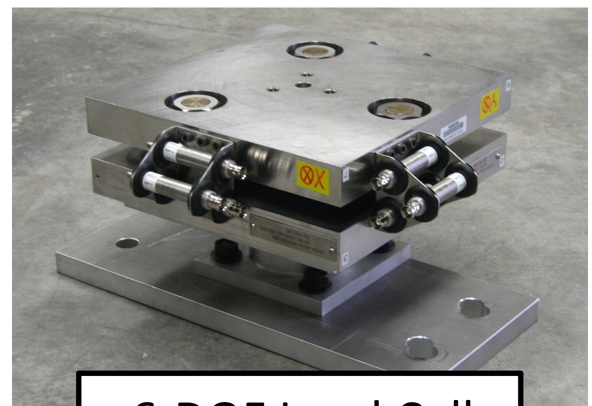


DIM Test Setup

Test Article on Soft Supports



Seismic Accels



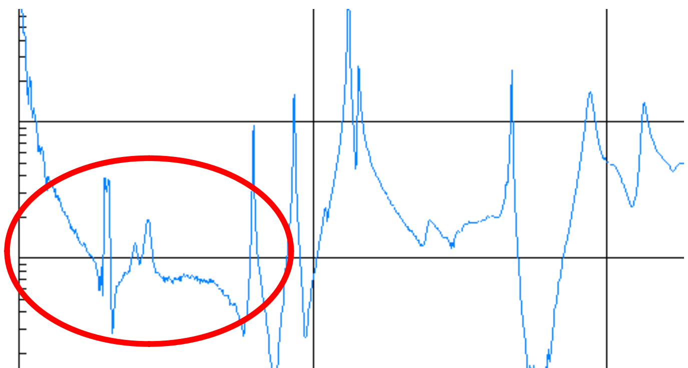
6-DOF Load Cell

DIM Testing

- Evaluated test methods
  - Sensors
    - Seismic accelerometers
    - 6 degree-of-freedom load cells
  - Excitation techniques
    - Impact hammer vs. shaker excitation
    - Force levels
    - Excitation locations
  - Data collection techniques
- Used ATA's analysis scripts for DIM analysis

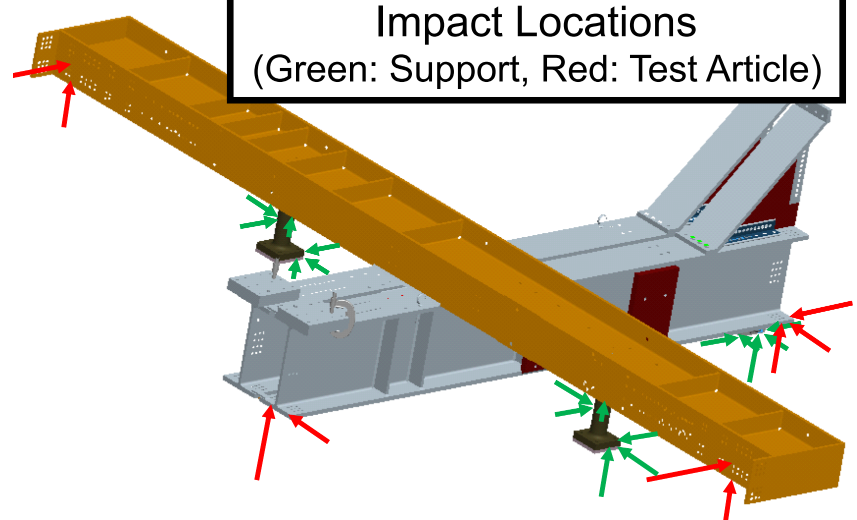
Impact Excitation

- Impact hammer used at 13 locations
  - Poor signal-to-noise ratio in lower frequency range
  - Measured first flexible mode at 17 Hz
  - Measured pedestal flexible mode at 6 Hz
- Performed step relaxation/free decay measurement
- Performed long periods of random impact excitation
  - All forces measured through 6-DOF load cells



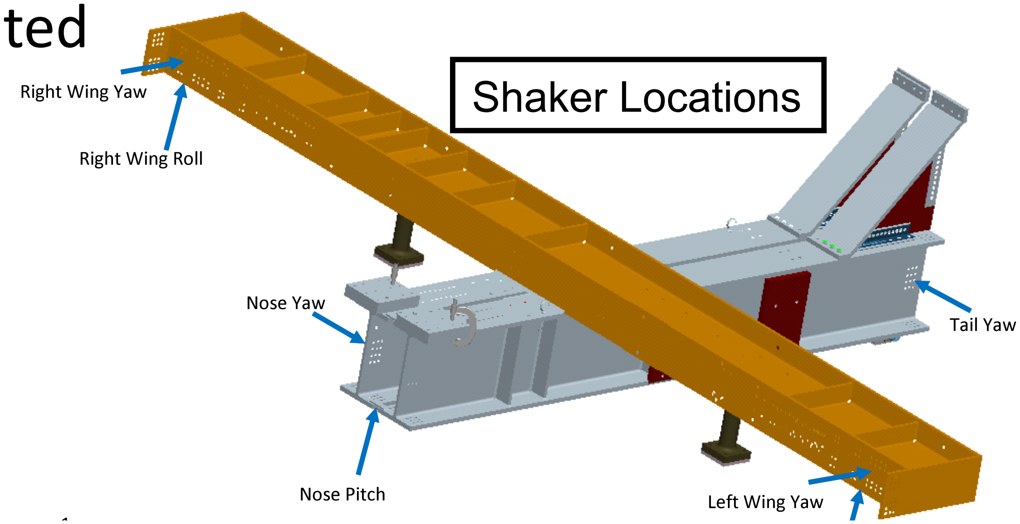
Impact Hammer –
Noise in Lower Frequency Range

Impact Locations
(Green: Support, Red: Test Article)



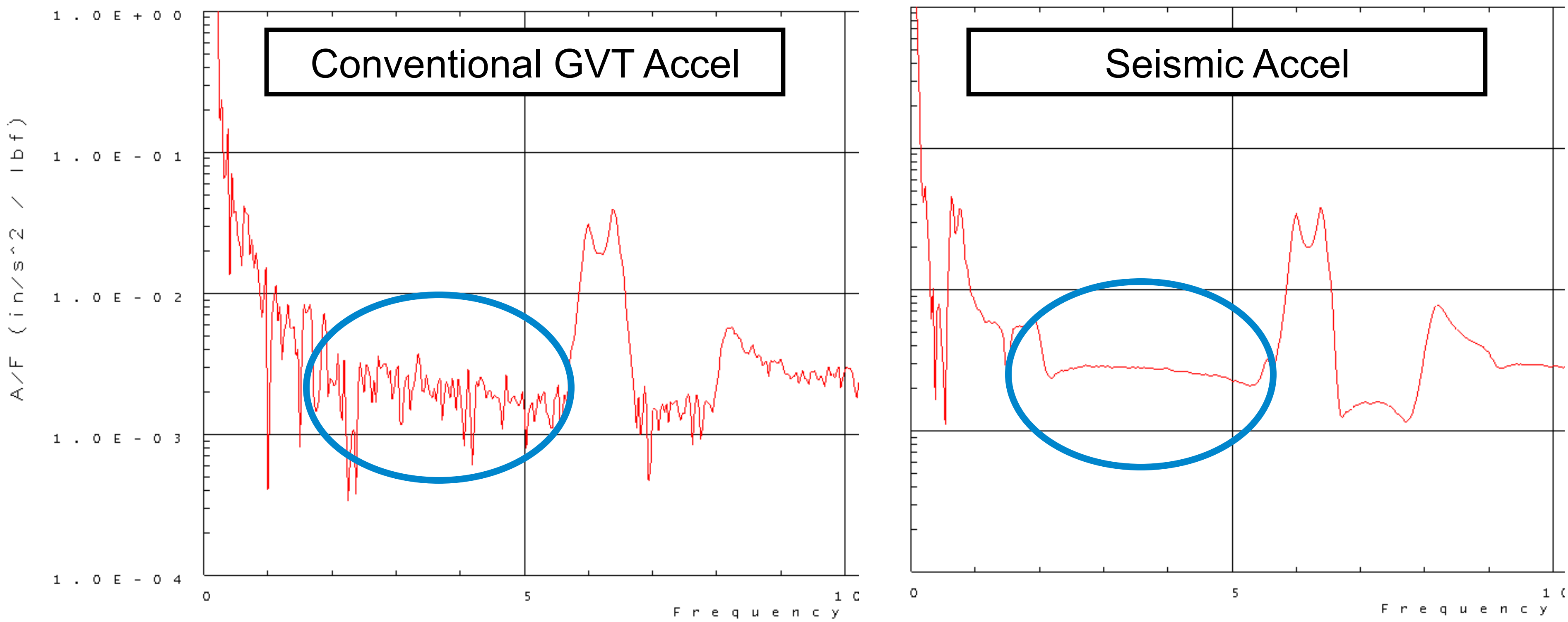
Shaker Excitation

- Collected data by exciting with shaker at 7 locations
- Initially used burst random shaker excitation
  - Response did not damp out; produced noisy data
- Continuous random excitation improved data quality
  - Used continuous random with window from 0-100 Hz
  - Performed an additional test run at each location for 1-8Hz to concentrate energy at lower frequency range
- Different force levels evaluated
  - Low force levels were adequate for DIM analysis
  - Switched to smaller shaker for easier handling

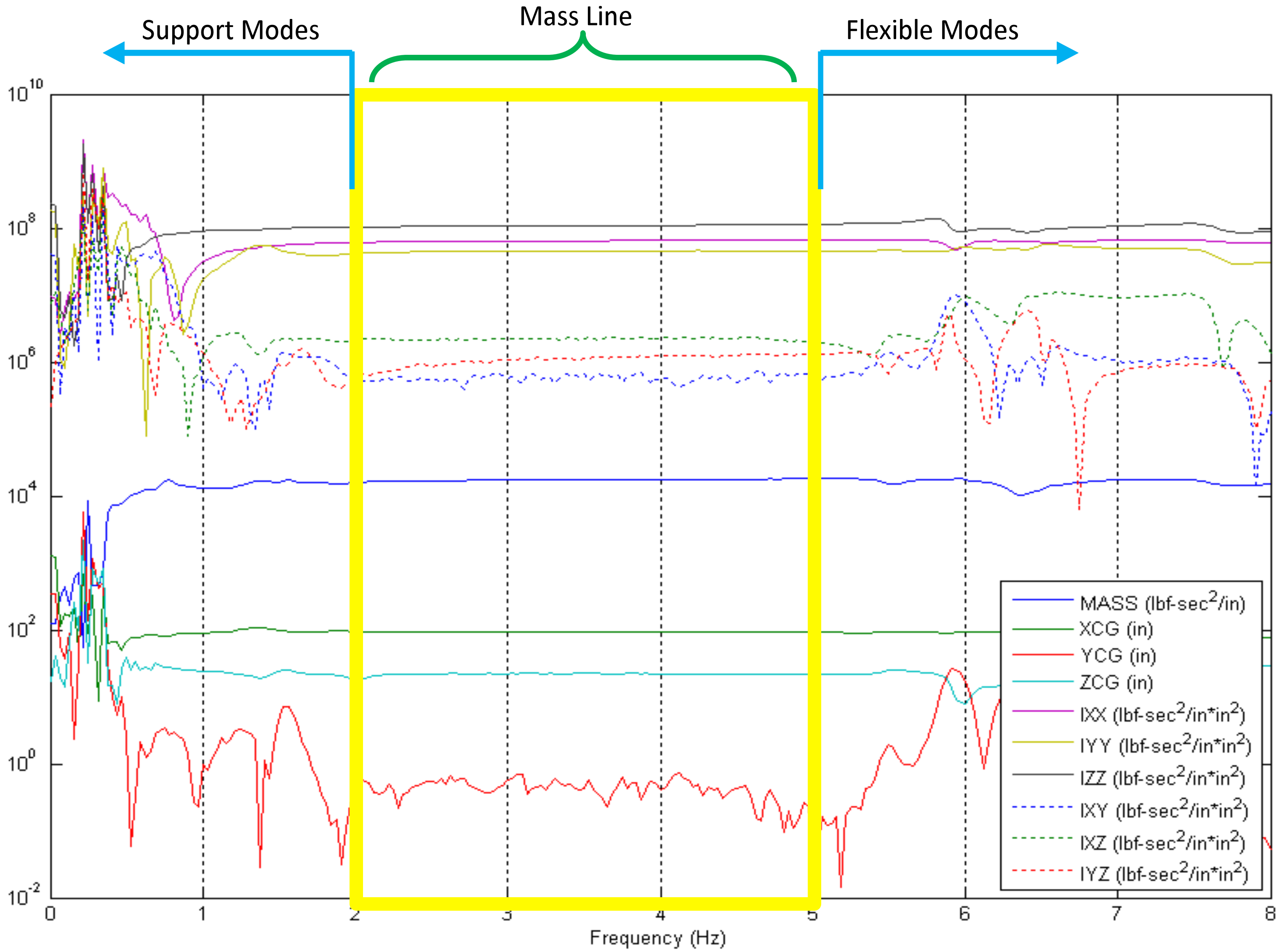


Seismic Accelerometers

- Seismic accelerometers were able to measure mass line structural response with much lower noise than conventional accelerometers



DIM Results (continued)



DIM Results

- Analytical Values
  - CAD model update performed to match bifilar values for X-cg and Izz
  - Mass properties of DIM related hardware added analytically
- Reasonable correlation between analytical and DIM values for most properties
  - Details of test configuration reduced certainty of results
  - Anticipating greatly improved accuracy with next iteration of testing

Comparison of Analytical and DIM Values

Property	NASA Estimations	DIM Method	% Difference
Weight (lbf)	16882	17331	-2.66%
Xcg (in)	91.39	91.51	-0.13%
Ycg (in)	-0.17	-0.43	0.26
Zcg (in)	23.33	22.01	5.67%
Ixx (lbm-in^2)	5.68E+07	6.42E+07	-12.98%
Iyy (lbm-in^2)	4.66E+07	4.52E+07	2.96%
Izz (lbm-in^2)	9.67E+07	1.08E+08	-11.64%

Lessons Learned

- Several key questions were answered in regards to excitation and instrumentation
  - Shaker excitation with continuous random signal is best for DIM
  - Low excitation force required
  - Seismic accelerometers provided good DIM response
  - Good sensor coverage of lowest flexible modes is a must for successful use of spatial filtering
  - 6-DOF load cell worked well, but design could be improved
- Modes in test support equipment interfered with results
  - Pedestal adapters to isolation system
  - Multiple flexible modes from 6-12 Hz
    - Below first flexible mode of test article (17 Hz)
    - Unable to be filtered out
  - Reduced DIM analysis window

DIM Conclusions

- Some aspects need further consideration for DIM application on large test articles
  – A different 6 degree-of-freedom load cell design should be considered
  – Spatial filtering requires adequate instrumentation to fully measure first flexible modes
  – Care should be taken to anticipate/measure non-structural component modes lower than first flexible mode
- Another large-scale test is planned for 2011